Toward a Global 1/25° HYCOM Ocean Prediction System with Tides

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LONG-TERM GOALS

The overall technical goal is to implement a 1/25° horizontal resolution global ocean prediction system based on the HYbrid Coordinate Ocean Model (HYCOM) with tides and dynamic sea ice. The scientific goals include but are not limited to a) evaluation of the internal tides representation in support of field programs, b) data assimilation in the presence of tides, c) evaluation of the model's ability to provide useful boundary conditions to high resolution coastal models, d) interaction of the open ocean with ice, e) shelf–deep ocean interactions, f) upper ocean physics including mixed layer/sonic depth representation, g) mixing, etc.

OBJECTIVES

Perform the R&D necessary to develop, evaluate, and investigate the dynamics of 1/25° global HYCOM with tides coupled to CICE (the Los Alamos sea ice model) with atmospheric forcing only, with data assimilation via NCODA (NRL Coupled Ocean Data Assimilation), and in forecast mode. Work closely with NRL Stennis to incorporate advances in dynamics and physics from the science community into the HYCOM code maintained by the Navy.

APPROACH

A series of HYCOM configurations is used to (a) evaluate internal tides representation, (b) implement a configuration for data assimilation in the presence of tides, and (c) investigate the interaction of the open ocean with ice. HYCOM development is the result of collaborative efforts among the Florida State University, University of Miami, and the Naval Research Laboratory (NRL) as part of the multi-institutional HYCOM Consortium for Data-Assimilative Ocean Modeling (Bleck, 2002; Chassignet et al., 2003; Halliwell, 2004). This effort was funded by the National Ocean Partnership Program (NOPP) to develop and evaluate a data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model (Chassignet et al., 2009). HYCOM has been configured globally and on basin scales at up to 1/25º (~3.5 km mid-latitude) resolution. More details on the latest global simulations can be found at http://www.hycom.org and in the separate ONR report on NRL activities by A. Wallcraft.

Report Documentation Page

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1. REPORT DATE 2010	2. REPORT TYPE	3. DATES COVERED 00-00-2010 to 00-00-2010

4. TITLE AND SUBTITLE
Toward a Global 1/25degree HYCOM Ocean Prediction System with Tides

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Florida State University,Center for Ocean-Atmospheric Prediction Studies,Tallahassee,FL,32306-2620

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**13**	

RESULTS

Internal wave representation in Oceanic General Circulation Models (OGCMs)

In order to investigate the impact of the model grid spacing and vertical coordinate choice on the representation of internal waves in OGCMs and HYCOM in particular, we performed a multi-model study of internal wave generation, propagation and evolution. The configuration is a stratified channel with a barotropic tide interacting with a Gaussian ridge (Khatiwala, 2000; Di Lorenzo et al., 2003; Legg and Huijst, 2006). The models that were evaluated are the HYbrid Coordinate Ocean Model (HYCOM, hybrid vertical coordinate), the Regional Ocean Modeling System (ROMS, terrain-following vertical coordinate), and the MITgcm (geopotential vertical coordinate). These models were chosen because of their different vertical coordinates and their wide usage by the community for global, regional, and coastal applications. Figure 1 shows the cross-vertical section of the zonal baroclinic velocity after 5 days for HYCOM (run in a fully isopycnal mode) and ROMS for different horizontal grid spacing and for a particular critical wave regime (the steepness parameter, ratio of the topography slope to the internal wave beam angle, is close to 1). Results for the MITgcm are not shown. The results show a good agreement with the theoretical results at high horizontal resolution, but the baroclinic response is considerably weaker at coarse horizontal resolution since the models are unable to resolve the higher internal wave modes. Spatial wavelet analysis of the bottom baroclinic velocities shows this loss of energy at coarser resolution, but also that the wave speed is less impacted by the change of resolution (not illustrated). In ROMS with the coarse horizontal resolution, the grid stiffness ratio parameter is violated and smoothing of the bathymetry is required. Such smoothing can lead to an underestimation of the tidal conversion process up to 50% (Di Lorenzo et al., 2003).
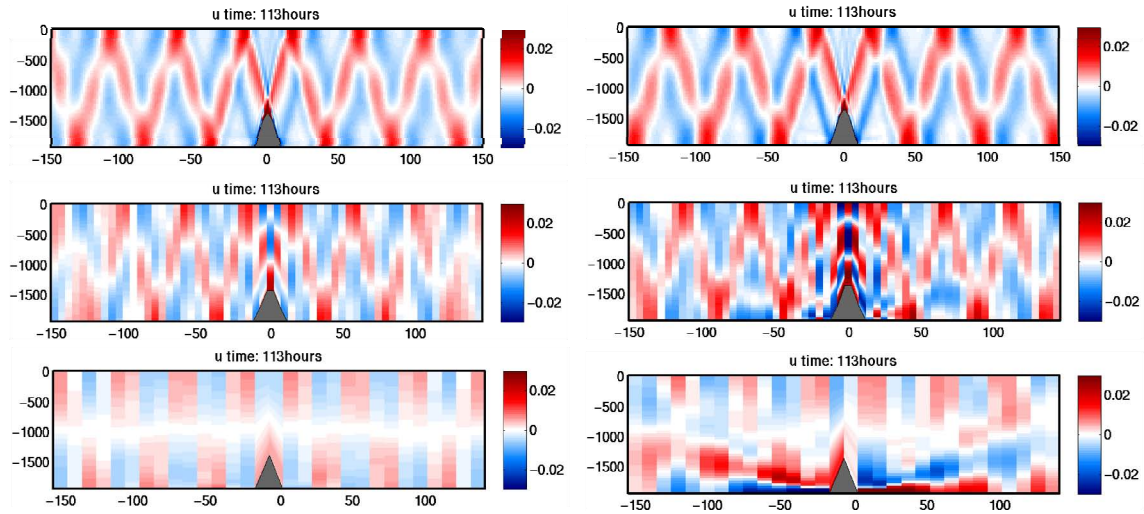

Figure 1: Snapshots (~4.7 days) of cross-vertical section of zonal baroclinic velocity for HYCOM (left panels) and ROMS (right panels). The horizontal model resolution is Δx =1.5 km for top panels, Δx = 5 km for middle panels, and Δx = 10 km for bottom panels. There are 100 layers/levels (Δz = 20 m) in the vertical for both models.

Diagnosing spurious mixing in fixed coordinate ocean models

Due to their numerical formulation, fixed vertical coordinate models are not able to preserve adiabatic properties of advected water parcels (Griffies et al., 2000). This numerically-induced diapycnal mixing

can in some cases be of the same magnitude as naturally occurring mixing. There are only few studies that attempt to document and quantify this spurious diapycnal mixing (Griffies et al., 2000; Morales Maqueda, 2007; Holloway, 2007; Riemenscheider and Legg, 2007; Burchard and Rennau, 2008). This study aims to document and quantify this spurious mixing for two idealized cases using ROMS and the MITgcm: 1) the well known lock exchange problem (Haidvogel and Beckman, 1999), and 2) a pure internal wave field as described in the previous section. For both experiments, no explicit mixing is prescribed and thus only the initial water masses should remain at all times. We use the tracer flux method described by Griffies et al. (2000) to compute the spurious numerically-induced diapycnal diffusivity for both scenarios. This work was performed by F. Gouillon who defended his Ph.D in summer 2010. A paper is in preparation (Gouillon and Chassignet, 2010).

Data assimilation and tides

Assimilation systems typically consist of multiple interacting components for data handling, pre/post-processing module and analysis. The assimilation schemes available for HYCOM were all developed independently by the different assimilation groups and each of these schemes use different data formats, file naming conventions, metadata and interfaces between the different components. Early on, faced with the situation of handling multiple data formats and interfaces, we quickly realized that in order to be able to compare these schemes, we needed to standardize their data flow and data handling infrastructure. This led to the development of a HYCOM "data assimilation toolbox" (Srinivasan et al., 2010). This "toolbox" is actually configured for the Gulf of Mexico (GOM) which is an ideal setting for exploring the performance of assimilation schemes because of its circulation features, limited size, data availability and interesting dynamics. Due to its limited size, the size of the state vector in high-resolution GOM-HYCOM configurations is O (10^6-10^7). Therefore, computationally expensive advanced assimilation schemes which require on the order of O (50-100) concurrent model runs can be tested in combination high-resolution GOM-HYCOM configurations. Further, the GOM is well sampled by both remotely sensed and in-situ data.

In order to be able to test the ability of data assimilation schemes to perform in the presence of tides, we added tides to the "toolbox". We used the 1/25° resolution of the Navy Research Laboratory Gulf of Mexico HYCOM configuration with 20 layers. The eastern and southern boundaries are nested to the global 1/12º HYCOM. In order to avoid reflections due to the tides at the boundaries, a radiative *Flather* condition is applied on the barotropic components of the velocity. The atmospheric forcing is given by the Navy Operational Global Atmospheric Prediction System (NOGAPS). The barotropic tidal transport and elevation are prescribed at the open boundaries and are derived from the Egbert and Erofeeva (2002) model. Good agreement is found between GOTT99 and the model solutions (Figure 2).
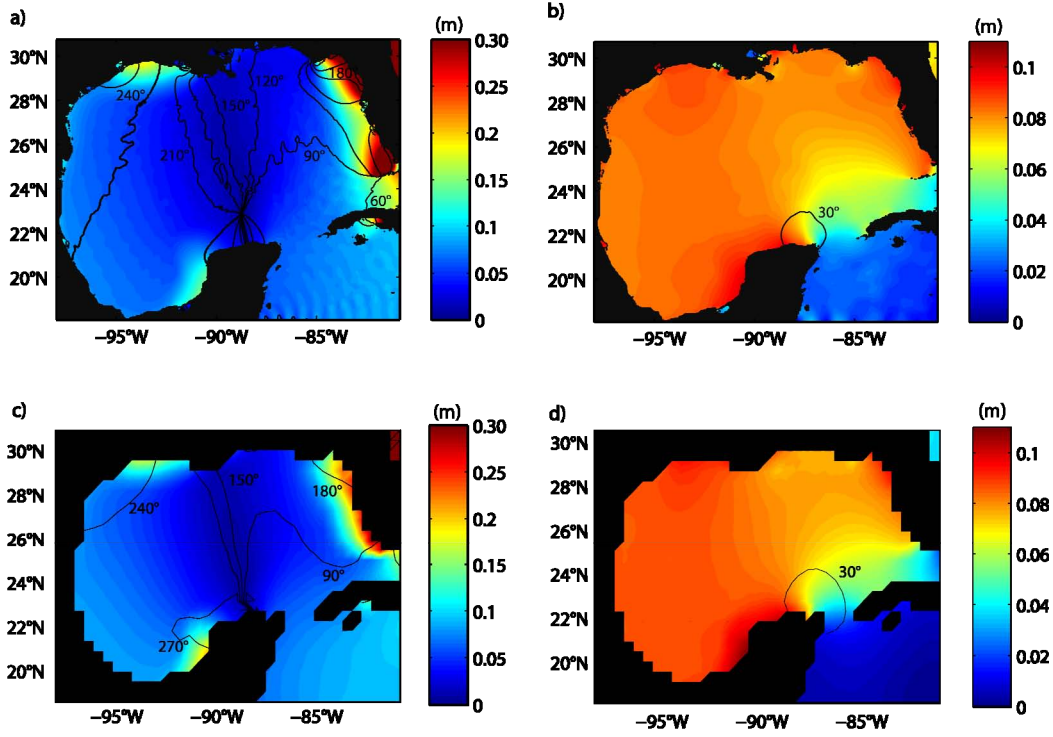
Figure 2: Maps of tidal amplitudes (colored) and phases (contoured) for: a) the M2 tidal constituent, b) the O1 tidal constituent, c) M2 from GOT99, and d) O1 from GOT99. Amplitudes are in meters and phases in degrees.

Bias and drift of water properties are common problems in numerical ocean models. They can cause the realism of a model's time-averaged state to fade with time and this can negatively impact the model's usefulness in terms of both short-term forecasting and multi-year hindcasting. Recently, Thompson et al. (2006) proposed a simple, statistically-based method for suppressing the bias and drift of basin-scale ocean circulation models and illustrated the technique using an eddy permitting model of the North Atlantic forced with realistic surface fluxes for the period 1991 to 2002. The method is based on the simple idea of nudging the model toward seasonal climatologies of ocean observations in specified frequency and wavenumber bands; outside of these bands the model is unconstrained. It falls within the class of sequential data assimilation methods based on the Kalman Filter. Thompson et al. (2006) outline a straightforward way of ensuring a model's climatology does not stray too far from an observed climatology, thereby suppressing bias and drift. The basic idea is to nudge the model in frequency and wavenumber bands that cover only the frequencies and wavenumbers resolved by the climatology. For this reason Thompson et al. (2006) called the technique spectral nudging, in accord with a method developed earlier by Von Storch et al. (2000) to downscale large-scale atmospheric states using high resolution regional atmospheric models. Outside of these frequency/wavenumber bands the nudging is effectively zero and the model can evolve prognostically, regardless of the strength of the nudging. This contrasts sharply to more conventional nudging schemes which suppress variability more strongly as increases. Their main conclusion of this study is that spectral nudging can be readily implemented into a fully nonlinear, 3D baroclinic circulation model to suppress bias and drift of the predicted temperature and salinity fields. They also implemented this method in a coastal model and found that the addition of spectral nudging resulted in improved tidal predictions in some regions and also allowed coastal upwelling and instabilities to occur about a seasonally evolving background state.

This concept of time scale separation can be applied to tides as well; and the data assimilation technique does not have to be nudging. This approach fits well with the HYCOM's existing sequential assimilation framework and we anticipate that implementation of this technique will be useful not only for multi-year hindcasts, but also for short-term forecasts in the presence of tides. This technique also allows the identification of model errors on various time scales. In a recent application of spectral nudging using an eddy permitting model of the North Atlantic, Wright et al. (2006) show how the distribution of the nudges can be useful in identifying model errors, thus pointing to an iterative method of model improvement.

Arctic Ocean

The major goal of the work is to develop, validated, and improve a fully coupled modeling system of the Arctic Ocean and sea ice. Within the AOMIP, COAPS will participate in coordinated AOMIP experiments and provide model results for community model intercomparisons and process study in the Arctic. For these purposes, a fully coupled Arctic Ocean – Sea Ice modeling system is being used. The coupled modeling system has been recently developed at Naval Research Laboratory Stennis Space Center (see Chassignet et al., 2009 for a review). The ocean model component is based on HYCOM (HYbrid Coordinate Ocean Model) which vertical discretization is a combination of isopycnic, terrain-following and geopotential vertical coordinates (Bleck, 2002; Chassignet et al., 2003). The sea ice component is based on CICE 4 sea ice model (Hunke and Lipscomb, 2004). The model uses Arctic dipole grid with two configurations: 0.72 degree (ARCc 0.72) and 0.08 degree (ARCc 0.08) horizontal resolution (Figure 3).

From the previous analysis of ARCc0.72 hindcast run 2003-2006 performed by NRL SSC (experiment 060), it follows that the model has failed to simulate distribution and thermohaline characteristics of the Atlantic water (defined as water mass with T > 0˚C) in the Arctic Ocean (Figure 4, right panel). In that simulation, warm Atlantic water does not penetrate in the Arctic Basin in contradiction with the climatology fields (Figure 4, middle panel). From observations and other model studies, the Atlantic water flows along the shelf edge in Eurasian Basin in cyclonic sense and spreads over the Canada Basin forming warm layer with temperatures above 0°C in the depth range from ~ -800 to -150 m. In the hindcast run conducted at NRL SSC, Atlantic Layer is cold in the Eurasian Basin. A strong negative anomaly in the temperature field at 200 – 700 m off the Kara Sea shelf is simulated in the model (Figure 3a). These results suggest that Atlantic water circulation is misrepresented in the model.

One possible reason for disagreement between model results and observations is misrepresentation of geomorphology of the Arctic Basin in ARCc0.72 experiment 060 (Figure 5): Eurasian shelves are closed (the coastline is at 50 m depth); major channels in the Canadian Arctic Archipelago are not resolved; Bering Strait is closed. These artificial alterations in the basin's topography might have affected the mesoscale circulation in the Arctic Ocean leading to different distribution of water masses compared to climatological fields. To test this hypothesis, we have reconfigured ARCc0.72 with improved bathymetry (Figure 5) and run the model for 2003 -2009 (experiment 040). During the simulation, same forcing fields are employed as in experiment 060 (NRL experiment). The model is started from rest with T/S fields from PHC 3 climatology (*http: //psc.apl.washington.edu/POLES*). The model is run 1 year with climatological forcing and 6 years with repetitive 0.5 degree 3-hourly NOGAPS atmospheric fields (Goerss and Phoebus, 1991; Bayler and Lewit, 1992) for 2003. At the lateral OBs, the model is relaxed to the climatological fields. At the surface, the model is forced with 0.5 degree 3-hourly NOGAPS atmospheric fields.

In the experiment 040 with improved representation of bathymetry, the Atlantic water propagates into the Arctic Basin. The warm layer is formed in the Eurasian Basin and Canada Basin within the depth range from -900 to -200 m, in general agreement with climatological data (Figures 4, 6, and 7). More accurate distribution of the Atlantic water in the Arctic Basin in experiment with improved bathymetry stems from more realistic mesoscale circulation in experiment 040. In this experiment, Atlantic water propagates into the basin through the Fram Strait and Barents Sea and flows along the shelf edge (Figure 8). This did not occur in the previous simulation (experiment 060). Most of warm Atlantic water recirculated in the Greenland Sea with very little fraction passing through the Fram Strait. The Barents Sea branch had noticeably smaller heat transport in the previous experiment. This resulted in depleted warm layer in the Arctic Ocean simulated in experiment 060.

We are currently analyzing results to explain different flow patterns in the two experiments. A manuscript focusing on the effect of topography representation on mesoscale circulation in the Arctic Ocean models is under preparation. A detail analysis will be conducted on water mass distribution in the model, which may suggest other adjustments in the model (e.g., different target densities, number of vertical layers, different OB conditions, etc) with additional numerical experiments.
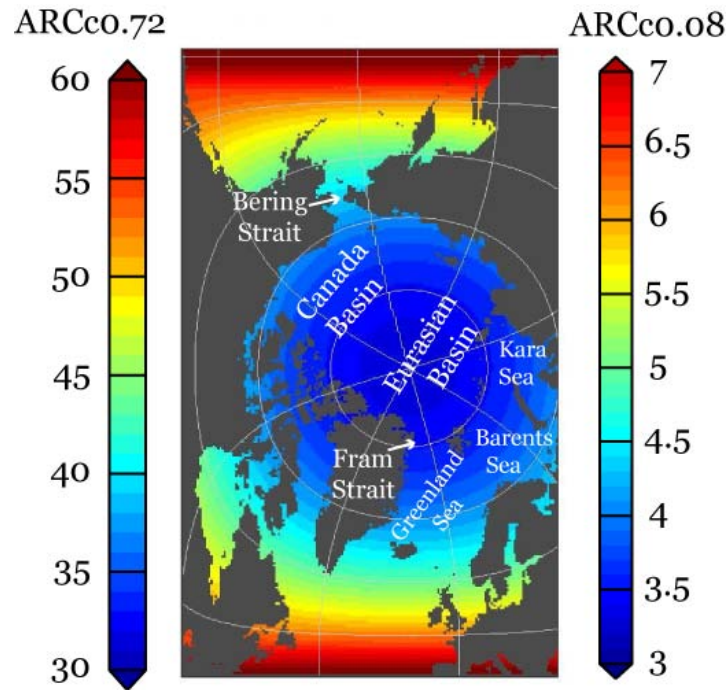

Figure 3. Model domain of HYCOM/CICE modeling system of the Arctic Ocean (ARCc). Colors show horizontal resolution for 0.72° (left colorbar) and 0.08° (right) configurations of ARCc.
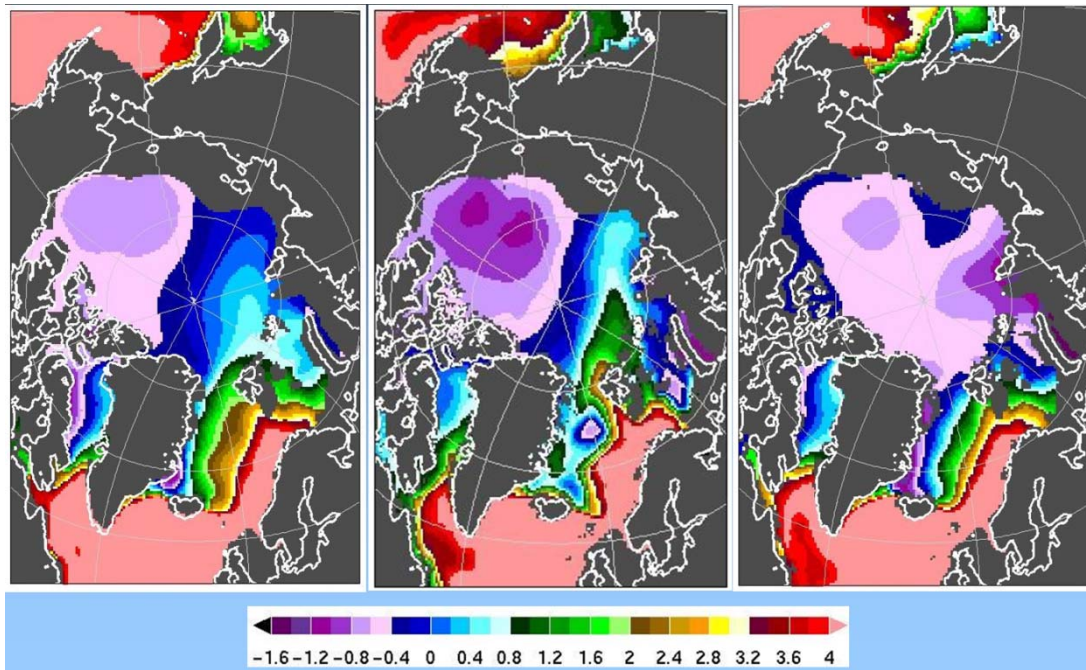
Figure 4. Annual temperature field at 200 m. Left: ARCc0.72 experiment 040 (2006); Middle: GDEM climatology; Right: ARCc0.72 experiment 060 (2006). Note negative bias in the Eurasian Basin in experiment 060, which is absent in experiment 040.
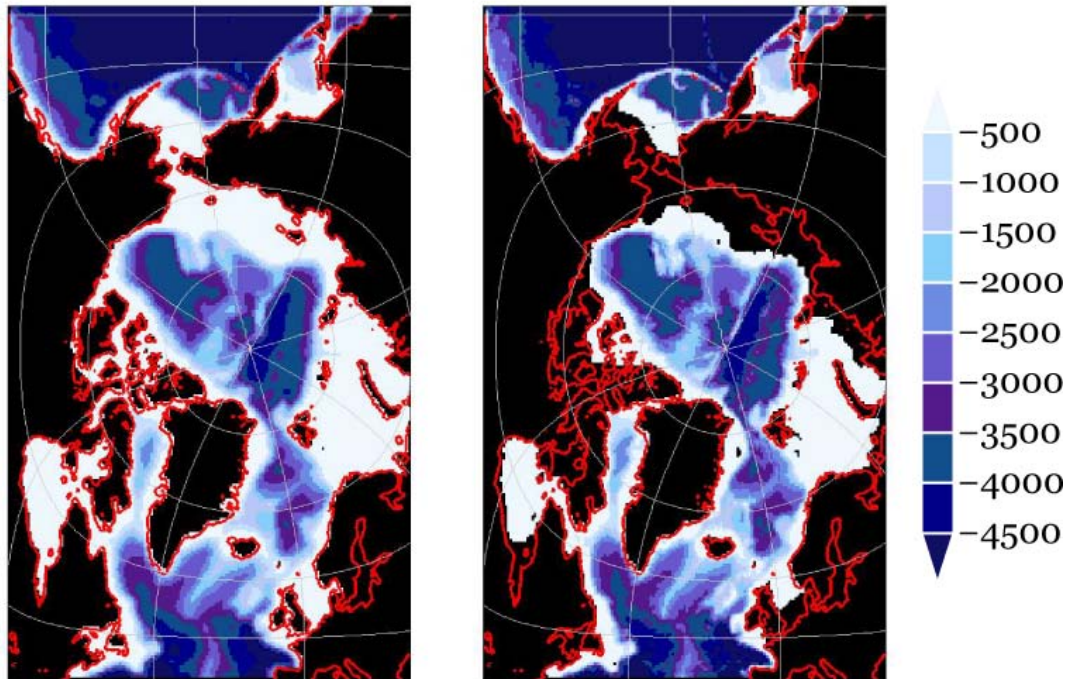

Figure 5. Model bathymetry of the ARCc0.72. Left: model domain in experiment 040 (COAPS) bathymetry: open Bering Strait, shallow coastline (10 m) resulting in a better representation of the Siberian shelf, better resolved channels in the Canada Arctic Archipelago. Left: model domain in experiment 060 (NRL SSC). The red line delineates ETOPO 2 coastline.
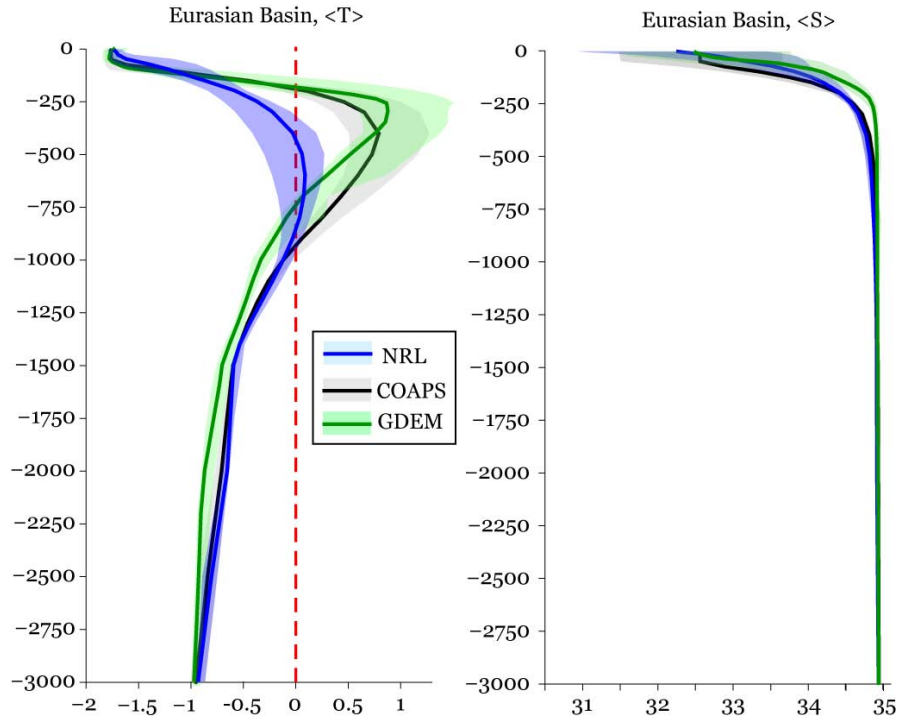
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Figure 6. Temperature (left) and salinity (right) profiles spatially averaged over the Eurasian Basin. Solid lines indicate results from ARCc0.72 experiment 040 (black), 060 (blue) and GDEM climatology (green). Shades delineate 10 – 90 % range of the data. Note the Atlantic Layer (positive T) is markedly well simulated in experiment 040 compared to GDEM profile.
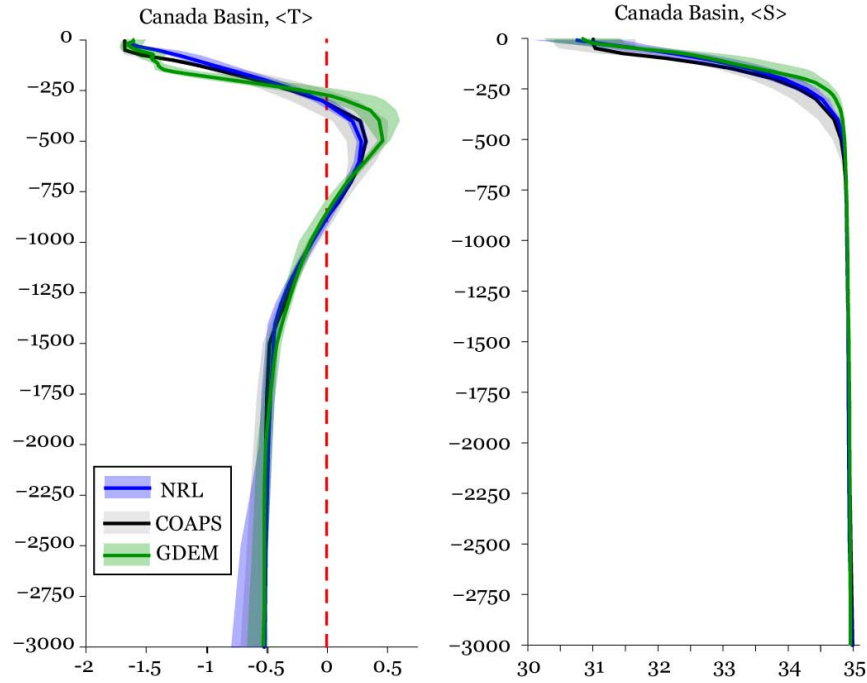

Figure 7. Temperature (left) and salinity (right) profiles spatially averaged over the Canada Basin. Solid lines indicate results from ARCc0.72 experiment 040 (black), 060 (blue) and GDEM climatology (green). Shades delineate 10 – 90 % range of the data.
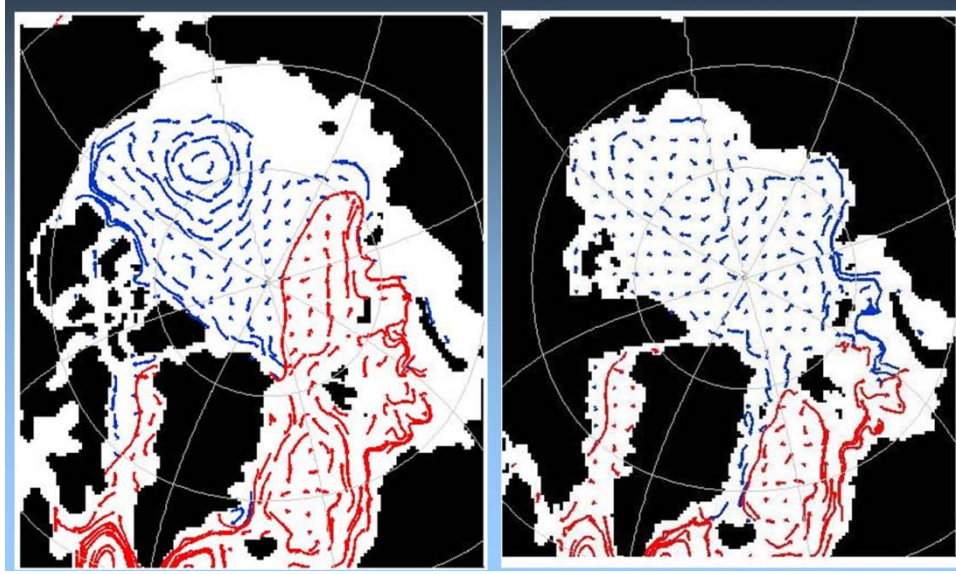
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Figure 8. Particle trajectories at 200 m from the annual mean velocity field simulated in the experiment 040 (left) and 060 (right). Red arrows indicate flow of water with positive temperature.

Mixed Layer Salinity Budget and Sea Ice in the Sourthern

The seasonal variation of mixed layer salinity budget in the Southern Ocean has been evaluated over the latitude range 45ºS-62ºS using Argo profiling float data, freshwater flux (evaporation minus precipitation [E-P]), geostrophic velocity, wind stress and sea ice concentration observations (Ren et al., 2010). The mixed layer salinity has a strong seasonal cycle, driven by seasonality in E-P, Ekman advection, entrainment, and sea ice. Over large areas, the geostrophic advection and diffusion show smaller contributions to the seasonal variation relative to other terms. The air-sea freshwater flux and Ekman advection in this area generally result in net decreases in salinity, while the entrainment term yields increases. Residual imbalance is consistent with a sea ice effect, whose contribution is evaluated. Sea ice is found to make a significant contribution, growing in importance toward the ice edge. We are curently repeating the analysis using the global HYCOM ouputs during the 2008-2010 period. This allows not only for an evaluation of HYCOM (See Figures 9, 10, and 11for an example), but also for an assessment of the technique used in Ren et al. (2010).
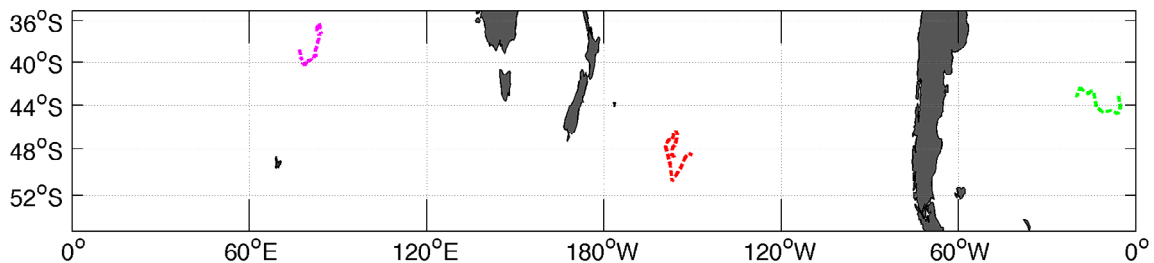

Figure 9: Three Argo profiling float trajectories with the WMO ID 1900722 in Indian Ocean sector (purple), WMO ID 5901383 in the Pacific Ocean sector (red), and WMO ID 3900606 in the Atlantic Ocean sector (green).
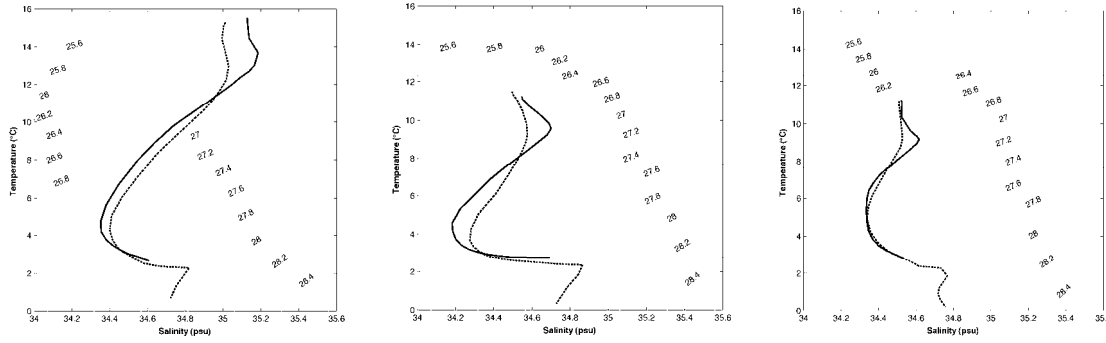
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Figure 10: The mean T/S plot of the profiles from Argo 1900722, 5901383, and 3900606 (solid line) and corresponding HYCOM profiles (dashed line).
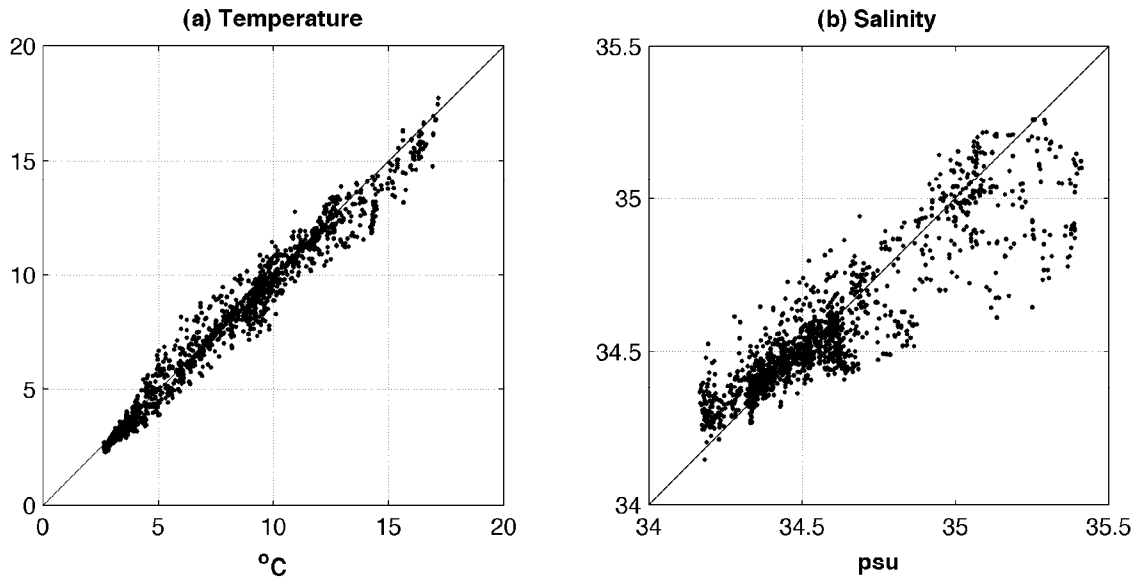

Figure 10: Scatter plots of HYCOM versus observations for the above ARGO flaots. (a) Temperature, (b) Salinity.

IMPACT/APPLICATIONS

The 1/25° (3.5 km mid-latitude) resolution, first used in some FY09 global HYCOM simulations, is the highest so far for a global ocean model with high vertical resolution. A global ocean prediction system, based on 1/25° global HYCOM with tides, is planned for real-time operation starting in 2012. At this resolution, a global ocean prediction system can directly provide boundary conditions to nested relocatable models with ~1 km resolution anywhere in the world, a goal for operational ocean prediction at NAVOCEANO. Internal tides and other internal waves can have a large impact on acoustic propagation and transmission loss (Chin-Bing et al., 2003, Warn-Varnas et al., 2003, 2007), which in turn significantly impacts Navy anti-submarine warfare and surveillance capabilities. At present, regional and coastal models often include tidal forcing but internal tides are not included in their open boundary conditions. By including tidal forcing and assimilation in a fully 3-D global

ocean model we will provide an internal tide capability everywhere, and allow nested models to include internal tides at their open boundaries.

TRANSITIONS

None.

RELATED PROJECTS

The computational effort is supported by DoD HPC Challenge and non-challenge grants of computer time. In FY10, 1/25° and 1/12° global HYCOM ran under the FY09-11 DoD HPC HYCOM Challenge grant.

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